CNGS experimental programme

J. Marteau

CNGS EXPERIMENTAL PROGRAMME

J. MARTEAU
Institut de Physique Nucléaire de Lyon, IN2P3-UCBL
43, bd du 11 novembre 1918
69622 Villeurbanne, FRANCE
E-mail: marteau@ipnl.in2p3.fr

We discuss two experiments – OPERA and ICARUS – that have been proposed for the direct observation of the ν_τ appearance from the $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the CNGS neutrino beam. Neutrinos are produced at the CERN SPS with an average energy of 17 GeV and are directed towards the Gran Sasso Laboratory 730 km away.
This european long baseline programme aims at further understanding of the deficit seen in the atmospheric neutrinos experiments both in the ν_μ to ν_e flavor ratio and in the ν_μ zenith angle distribution. It aims at very high sensitivity in the parameter region suggested by the atmospheric neutrinos experiments and in particular by Super-Kamiokande. It also foresees a sensitive $\nu_\mu \leftrightarrow \nu_e$ appearance programme to perform an analysis of neutrino oscillation with three-flavour mixing. The direct observations of the oscillation products provide an unique tool to firmly assess the neutrino oscillation scenario.

1 Introduction

The possibility of a non-vanishing neutrino mass is one the most exciting problem of particle physics, astrophysics and cosmology. This possibility has been revealed a few years ago by the experiments dedicated to the observation of the atmospheric neutrinos [1,2,3]. Their data show consistently that the ν_μ produced in the atmosphere at the antipodes of the detector ("upwards" neutrinos) are depleted compared to those reaching the detector directly from above ("downwards" neutrinos). The best fit to the data is given by the neutrino oscillation of the ν_μ into another type of neutrino. The CHOOZ experiment [4] excludes the explanation in terms of $\nu_\mu \leftrightarrow \nu_e$ oscillations in the parameter region suggested by the experimental results, leaving open the $\nu_\mu \leftrightarrow \nu_\tau$ or possibly $\nu_\mu \leftrightarrow \nu_{\mathrm{sterile}}$ cases. The results of Super-Kamiokande, which has the largest statistics, favour the oscillations of the ν_μ into the ν_τ.

The best fit to the Super-Kamiokande [1] data, with "disappearance" probabilities expressed in the form :

$$P_{\nu_\mu\,\mathrm{disappearance}} = 1 - \sin^2(2\theta)\,\sin^2(\frac{\Delta m^2}{4} L E^n) \qquad (1)$$

where L is the oscillation pathlength between the source and the detector and E the neutrino energy, leads to the following values of the oscillations parameters :

$$\sin^2(2\theta) = 1, \quad \Delta m^2 = 3.2 \times 10^{-3}\ \text{eV}^2, \quad \text{and} \quad n = -1 \tag{2}$$

The 90% CL region consistent with 3.2×10^{-3} eV^2 as central value is :

$$\sin^2(2\theta) > 0.\text{[illegible]} \quad \Delta m^2 \in [1.5, 5]\, 10^{-3}\ \text{eV}^2 \tag{3}$$

Although the disappearance of the ν_μ is now well established, a complete neutrino pattern is still missing which would firmly assess the oscillation scenario. In particular only ν_μ *disappearance* have so far been observed. These observations should be extended by the disappearance long baseline programmes in Japan (the K2K experiment [5], from the KEK accelarator to Super-Kamiokande) and in the United-States (the MINOS experiment [6], from Fermilab to the Soudan mine). But the most convincing and unambiguous signal for flavor oscillation remains the detection of the oscillation product, namely a ν_τ in our present understanding. Furthermore, analysis have been performed by taking into account two families. Allowing a third family in the mixing scenario could also open the possibility that $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_e$ oscillations take place simultaneously. The present limits on the corresponding mixing parameter (U_{e3}) could therefore be improved.

The ν_τ and ν_e appearance programme in the CNGS beam from CERN to Gran Sasso is the aim of the OPERA [7] and ICARUS [8] experiments that we will describe in the following. This paper is organized as follows. Section 2 gives a brief presentation of the CNGS neutrino beam. Sections 3 and 4 are devoted to the presentation of the OPERA and ICARUS experiments. Section 5 gives the results for the sensitivity and the performance of these experiments.

2 The CNGS neutrino beam

The original CNGS reference neutrino beam from the CERN SPS to the Gran Sasso is described in Ref. [9]. Further optimisations have been studied and we refer to the version described in Ref. [10]. The graphite target is followed by two coaxial lenses, the horn and the reflector, a 1 km decay tunnel and a hadron stopper.
Two possible CNGS running modes are possible : i) the *shared mode*, in which both CNGS and fixed-target users are supplied with protons; ii) the *dedicated mode*, in which the CNGS is the only user. Assuming a 400 GeV/c proton beam and 200 days of running per year with $4.\text{[illegible]} \times 10^{13}$ protons per

cycle and 55 % overall efficiency, the expected number of *pot* is $4.5 \times 10^{19}/year$ in shared mode and $7.6 \times 10^{19}/year$ in dedicated mode. The nominal performance of the CNGS beam is given in Table 1. The number of ν_τ CC interactions per kton and per year (in a shared mode) is 30.4 for $\sin^2(2\theta) = 1$ and $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2.

Table 1. Nominal performance of the CNGS reference beam.

ν_μ (m^{-2}/pot)	ν_μ CC events/pot/kton	$\langle E \rangle_{\nu_\mu}$ (GeV)	ν_e/ν_μ	$\overline{\nu}_\mu/\nu_\mu$	$\overline{\nu}_e/\nu_\mu$
7.45×10^{-9}	5.44×10^{-17}	17	0.8 %	2.0 %	0.05 %

3 OPERA

3.1 Detector overview

In the OPERA experiment [7], the ν_τ detection is performed with nuclear emulsions as sensitive device. 50 μm thick emulsion layers are displayed on both sides of a 200 μm thick plastic base to form an emulsion sheet (ES). This structure allows to connect track segments left by the particles (around 15-20 silver grains of 0.6 μm diameter) on both sides of the base.

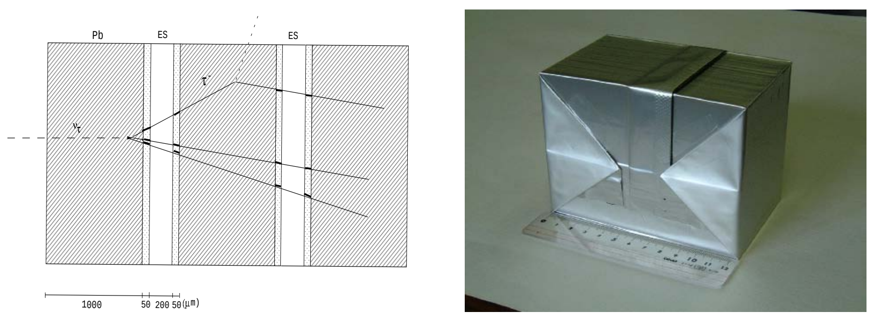

Figure 1. Left : schematic structure of an emulsion cell. The τ decay "kink" is reconstructed in space by using four track segments in the emulsion films. Right : a photograph of a brick with its packing.

These elementary *cell* structures are combined into a *brick* (10.2 × 12.7 ×

7.5 cm^3) by sandwiching them with 1 mm thick lead plates (Fig. 1). These plates constitute the passive material where most of the neutrino interactions occur. The bricks are arranged in *walls* of 6.8×6.8 m^2 cross-section, followed by two electronic tracker planes (x and y) devoted to the location of the brick where the primary interaction occured, to the reconstruction of penetrating tracks and to energy measurements. A succession of 24 walls + electronic trackers constitutes the *target section* of a *supermodule* which also contains a downstream muon *spectrometer*. The detector consists of a sequence of 3 supermodules in the baseline design (Fig. 2). The total mass of the target section amounts to $\sim$ 2 kton. The design of the detector where the target mixes dense passive material and emulsions, leads to a large fiducial mass required by the low statistics of the neutrino interactions (around 30 per day) while keeping the intrinsic high resolution of the emulsions.

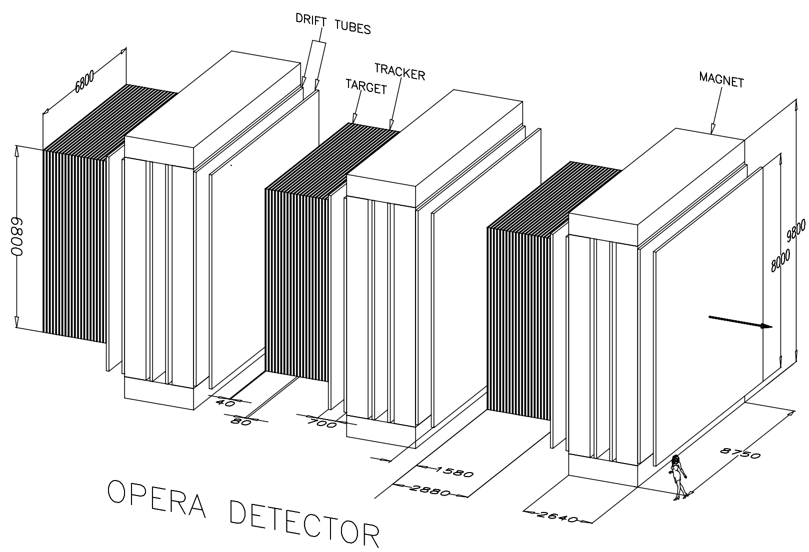

Figure 2. Schematic view of the OPERA detector.

3.2 τ detection

The signal of the occurrence of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations is the CC interaction of τ neutrinos in the detector target: $\nu_\tau N \rightarrow \tau^- X$. The reaction is identified by the detection of the τ lepton in the final state through its decay modes into an electron, a muon and a single charged hadron :

$$\tau^- \to e^- \nu_\tau \overline{\nu}_e, \quad \tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu, \quad \tau^- \to h^- \nu_\tau (n\pi^0) \tag{4}$$

The detection is based on the complete reconstruction of the τ decay topology, which exhibits a characteristic "kink" due to the two undetected neutrinos (Fig. 1). The intrinsic resolution of the nuclear emulsions (0.06 μm) provides an unique sensitivity to perform the topology reconstruction at the scale of the τ decay length ($\sim$ 1 mm).

3.3 Detector operation

During the run, electronic detectors placed downstream of each emulsion wall are used to select the brick where the neutrino interaction took place. The brick is then extracted by a brick handling machine. Removed bricks are exposed to cosmic muon flux for alignment purposes with an appropriate veto to distinguish cosmic tracks from event tracks. The bricks are then unpacked and stamped. Emulsions are automatically developped and scanned with microscopes. The scanning procedure has to : i) locate the neutrino primary vertex by scanning back all tracks starting from the most downstream emulsion layer (this is the more time consuming phase since the scanning area is large), ii) look for a decay topology near the primary vertex, iii) perform the full reconstruction of the ν_τ candidates (in some dedicated stations).

3.4 Scanning procedure

The detection technique with nuclear emulsions has benefited from the developments initiated first in Japan. The existence of automatic readout systems (Track Selector) and the availability of fast data processing (Net Scan) are the essential ingredients of the present technique which has been successfully tested in the large scale DONUT [11] and CHORUS [12] experiments, based on the same principle for the τ detection.
The basic algorithm of these systems consists in recording digitised tomographic images through the emulsion depth (typically 16 views for a 50 μm emulsion layer). One looks for the correlation of grains in the different views. The correlated grains are identified as a track segment. Two track segments on both side of a base are connected to form a base track. Then the connection between consecutive films is performed.
The structure of the cell is well suited also for momentum measurement through multiple scattering and for particle identification. The total energy of electrons and γ's is evaluated by the analysis of the shower development.

These analysis are required in particular for the τ candidates and they are completed by the informations of the electronic detectors placed downstream of each walls and of the spectrometer downstream of the target section.
Because of the large quantities of emulsions used in OPERA ($\sim$ 176000 m^2 compared to the 500 m^2 used in CHORUS) and although the track density in the detector will be far lower than in CHORUS or DONUT, an increase in the speed of the existing readout systems is required. For this purpose, a new Track Selector (*Super-UTS*) is being developped for OPERA. It aims at a scanning speed of 20 cm^2/h (20 times faster than the present systems).

4 ICARUS

4.1 Detector overview

The detector is constituted by a large liquid Argon TPC [8]. It combines the characteristics of a bubble chamber with the advantages of the electronic read-out.
The basic principle of the experiment relies on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. With a proper readout system (fine pitched wire grids), it is possible to obtain a massive "electronic bubble chamber" with superb 3D imaging.
This detector has excellent imaging capabilities, is isotropic and homogeneous. It is also continuously sensitive and self-triggerable. These features allow ICARUS to record not only the neutrinos coming from the beam but also atmospheric neutrinos. The large volume of the detector could also be used for other studies such as nucleon decay.
The performance in terms of dE/dx measurements give a good momentum measurement and particle identification. The electromagnetic and hadronic showers are also reconstructed with a good energy resolution and a good e/π^0 discrimination. The momentum can also be measured by the multiple scattering.

4.2 LAr state of the art

An extensive R & D programme was launched to control various aspects of the technique. Different small scale prototypes have been build and tested. Recently a module of 15 tons (*T15* prototype) has been operated in collaboration with industries. This prototype of 10 m^3 gives conclusive tests of the cryostat technology, the variable geometry wire chamber, the liquid phase purification system, the trigger via scintillation light, the readout electronics. An example of recorded tracks in this prototype is displayed in Fig. 3.

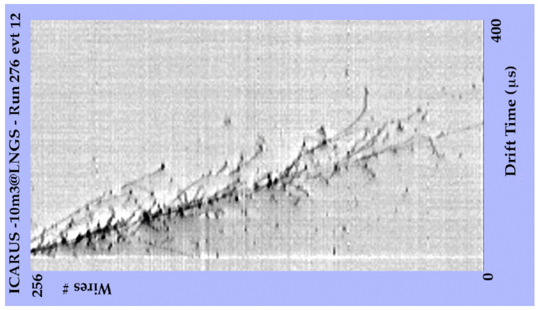

Figure 3. Example of recorded tracks in the T15 prototype. Particles come from the left. The vertical axis is the time (drift direction) and the horizontal one is the wire number.

The next step for the ICARUS collaboration is the construction of a 600 tons prototype (*T600*) to be installed at the Gran Sasso Laboratory in the year 2001.

5 Physics performance

5.1 Expected number of events in OPERA

As mentioned above, the τ is detected through its decay products in the electron-, muon- or hadron-1 prong channels. The decay channel into an electron benefits from the dense brick structure, which allows the electron identification through its showering. The muonic decay mode has a potential background from large angle scattering of the muon produced in ν_μ CC interactions that can be reduced by kinematical cuts on the kink angle and on the transverse muon momentum. Hadronic decay modes have the largest branching ratio but are affected by background due to hadron reinteractions. Kinematical cuts can be used to reduce this background.

An extensive simulation work has been undertaken in order to compute the overall detection efficiency of the experiment. The simulations have been tuned and refined to match the experimental data of the CHORUS and DONUT emulsion experiments but also of the NOMAD [13] experiment at CERN. The total efficiency is a product of various factors (wall and brick finding efficiencies, vertex finding efficiency, brick-to-brick connection, parti-

Table 2. Expected number of τ and background events in OPERA after five years of data taking ($2.25 \times 10^{20} pot$), at full mixing and for Δm^2 corresponding to the present best fit and 90% CL limits given by Super-Kamiokande.

τ decay mode	Signal ($1.5 \times 10^{-3} eV^2$)	Signal ($3.2 \times 10^{-3} eV^2$)	Signal ($5.0 \times 10^{-3} eV^2$)	BG
e^-	1.7	7.7	18.5	0.19
μ^-	1.3	5.7	13.8	0.13
h^-	1.1	4.9	11.8	0.25
Total	4.1	18.3	44.1	0.57

Table 3. OPERA sensitivities at the 90% CL on $\sin^2 2\theta$ at large Δm^2 and on Δm^2 at full mixing as a function of the years of data taking calculated according to the Feldman & Cousins approach [14]. The results obtained with the approach described in [15] for 5 years data taking are also shown.

	T.J. 5 years	F&C 5 years	F&C 2 years
$\sin^2(2\theta)$ at large Δm^2	6.3×10^{-3}	6.0×10^{-3}	1.4×10^{-2}
Δm^2 at $\sin^2(2\theta) = 1$	$1.3 \times 10^{-3} eV^2$	$1.2 \times 10^{-3} eV^2$	$1.9 \times 10^{-3} eV^2$

cle identification). Weighted by the branching ratio of the various detection channels, the global detection efficiency amounts to ~ 9 %.
The OPERA experiment is an almost background free experiment. The different sources of background mentioned above have been studied in details. The expected numbers of τ and background events are summarised in Table 2. The table shows that the signal/noise ratio ranges from 7 to 80.

5.2 OPERA sensitivity and determination of the oscillation parameters

The OPERA sensitivity at 90 % CL as a function of the oscillation parameters is displayed in Table 3.

The determination of Δm^2 by assuming full mixing and no additional constraints on the data analysis (such as the reconstruction of the event topology or the inclusion of other decay channels that could improve the sensitivity) is $\pm$ 19 % for $\Delta m^2 = 3.2 \times 10^{-3}$ eV^2 and $\pm$ 12 % for $\Delta m^2 = 5.0 \times 10^{-3}$ eV^2 at

90 % CL. This leads to a good improvement of the result deduced from the Super-Kamiokande data.

5.3 $\nu_\mu \leftrightarrow \nu_\tau$ *appearance with ICARUS*

The ν_τ events are searched through distortions in the visible energy spectrum of the leading electron sample (Fig. 4). The τ selection is based on kinematics as in the NOMAD experiment. The total number of ν_τ CC with subsequent $\tau \longrightarrow e\,\nu\,\nu$ is around 110 for $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2 to be compared to the 470 events expected from ν_e and $\bar{\nu_e}$ background events. Such excess is in principle visible before any cut is applied. After kinematical cuts these numbers become 35 for the ν_τ CC events and less than 6.1 for the background events.

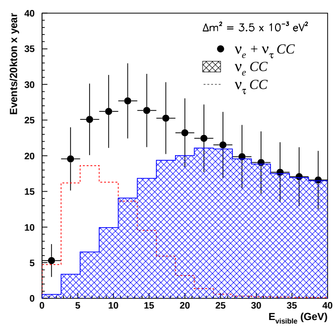

Figure 4. Expected reconstructed visible energy of events with leading electron in ICARUS. The filled histogram is the intrinsic ν_e, $\bar{\nu_e}$ contamination of the beam. The histogram is the ν_τ charged current with subsequent decay of tau into electron.

5.4 $\nu_\mu \leftrightarrow \nu_e$ *appearance in the three-flavour mixing*

If we consider three neutrinos, one squared mass difference (for example Δm^2_{12}) is attributed to the solar deficit while $\Delta m^2_{23} \simeq \Delta m^2_{13}$ is involved in the atmospheric neutrino deficit. This is one possible scheme. The parameterization of the mixing matrix implies that the amount of $\nu_\mu \leftrightarrow \nu_e$ oscillations is governed by the mixing angle θ_{13}.
Thanks to its excellent electron identification, the ICARUS experiment could look to an excess of events in the ν_e sample of events. After relevant kinematical cuts, the expected number of events for various values of θ_{13} are given in

Table 4.

Table 4. Rates for ICARUS from $\nu_\mu \to \nu_e$ oscillations in three family mixing. Here $\Delta m^2_{23} = 3.5 \times 10^{-3}$ eV^2 and $\theta_{23} = 45^o$. Rates are normalized to 4 years "shared" running of CNGS ($4 \times 4.5 \times 10^{19}$ pots).

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \to \nu_\tau$ $\tau \to e$	$\nu_\mu \to \nu_e$	Total	Statistical significance
9	0.095	79	74	84	237	6.8σ
8	0.076	79	75	67	221	5.4σ
7	0.058	79	76	51	206	4.1σ
5	0.030	79	77	26	182	2.1σ
3	0.011	79	77	10	166	0.8σ

This $\nu_\mu \leftrightarrow \nu_e$ appearance channel is also studied with the OPERA detector taking into account the good electron identification. The calculation of the detection efficiency and of the sensitivity in this channel is in progress.

6 Conclusion

The European CNGS programme long baseline neutrino programme is dedicated to the direct observation of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the neutrino beam from CERN to Gran Sasso. Two experiments, OPERA and ICARUS, are proposed to look for the appearance of ν_τ events. The first one is based on the nuclear emulsion technique with very high spatial resolution, allowing the direct observation of the tau decay topology as main signature of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation. This detection technique with unique features in terms of sensitivity and low background benefits from many improvements in the production, development and scanning procedures. The second is a liquid Argon TPC with a τ selection based on kinematics. Prototypes of various size have been successfully tested and the results of the T600 are expected for next year.
The experimental programme, which is extended to the search for $\nu_\mu \leftrightarrow \nu_e$ oscillations for a three-flavour analysis and to the parallel observation of atmospheric neutrinos, will bring an indispensable contribution to our understanding of neutrino physics. It is foreseen to start in 2005.

Acknowledgments

I thank A.Rubbia for material on ICARUS. I also thank the organizers of the IDM-2000 conference.

References

1. H. Sobel, [Super-Kamiokande Collab.], to appear on the Proc. of the XIX Int. Conf. on Neutrino Physics and Astrophysics, Sudbury, 16-22 june 2000;
   Y. Fukuda et al., *Phys. Rev. Lett.* **81** (1998) 1562;
   Y. Fukuda et al., *Phys. Rev. Lett.* **82** (1999) 5194.
2. A. Mann, [Soudan-2 Collab.], to appear on the Proc. of the XIX Int. Conf. on Neutrino Physics and Astrophysics, Sudbury, 16-22 june 2000;
   W.W.M. Allison et al., *Phys. Lett.* **B449** (1999) 137.
3. B. Barish, [MACRO Collab.], to appear on the Proc. of the XIX Int. Conf. on Neutrino Physics and Astrophysics, Sudbury, 16-22 june 2000;
   D.G. Michael (MACRO Coll.), Proc. of XXIX Int. Conf. on High Energy Physics (ICHEP), Vancouver, 1998.
4. M. Apollonio et al., *Phys. Lett.* **B420** (1998) 397;
   M. Apollonio et al., *Phys. Lett.* **B466** (1999) 415.
5. K. Nakamura, [K2K Collab.], to appear on the Proc. of the XIX Int. Conf. on Neutrino Physics and Astrophysics, Sudbury, 16-22 june 2000;
   The K2K experiment: *http : //neutrino.kek.jp/*.
6. E. Ables *et al.*, Fermilab Proposal P-875 (1995);
   NuMI-L-337 (1998); NuMI-L-375 (1998).
7. M. Guler *et al* [OPERA Collab.], "An appearance experiment to search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the CNGS beam", experimental proposal, CERN/SPSC 2000-028, SPSC/P318, LNGS P25/2000, July 10, 2000.
8. [ICARUS Collab.], "ICARUS: Proton Decay and the CERN-GranSasso Long Baseline Experiment", Proceedings of the "International Symposium on Lepton and Baryon Number Violation" Trento (Italy, Apr. 1998), Institute of Physics Publishing (1999), 321;
   F. Arneodo *et al.* [ICARUS and NOE Collab.], "ICANOE: Imaging and calorimetric neutrino oscillation experiment," LNGS-P21/99, INFN/AE-99-17, CERN/SPSC 99-25, SPSC/P314.
9. G. Acquistapace *et al.*, CERN 98-02, INFN/AE-98/05, 19 May 1998.
10. R. Bailey *et al.*, CERN-SL/99-034 (DI); INFN/AE-99/05.
11. M.Nakamura, *Nucl. Phys.* **B 77** (1999) 259.
12. E. Eskut et al. [CHORUS Coll.], *Phys. Lett.* **B434** (1998) 205.
13. P.F. Salvatore, Background Studies for the $\tau^- \to \pi^- \nu$ Channel Using the 1996 Flat-Top Muon Sample, NOMAD MEMO 98-002, 14 January, 1998.
14. G.J. Feldman and R.D. Cousins, *Phys. Rev.* **D57** (1998) 3873.
15. T. Junk, CERN-EP/99-041.